The Measurement of Q' by Head-Tail Phase Shift Analysis

BNL2002

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Outline

- Motivation

- The Head-Tail measurement principle

- The Head-Tail monitor of the SPS (2000)

- Improvements & Developments in 2001/2002

- Simulations and Robustness Study for LHC

- Conclusions

Motivation

LHC

- Problems with existing methods for Q' measurement

  → Variation of Beam Momentum and Tune Tracking

    - LHC momentum acceptance small

    - tight tolerances on betatron tune

  → Amplitude of synchrotron side-bands

    - Qs too low to distinguish side-bands from main tune peak

    - affected by resonant behaviour not linked to Q'

  → Width of betatron tune peak

    - requires knowledge of $\Delta p/p$

    - affected by other sources of damping/decoherence.

  ⇒ Test new "Head-Tail" technique in the CERN-SPS

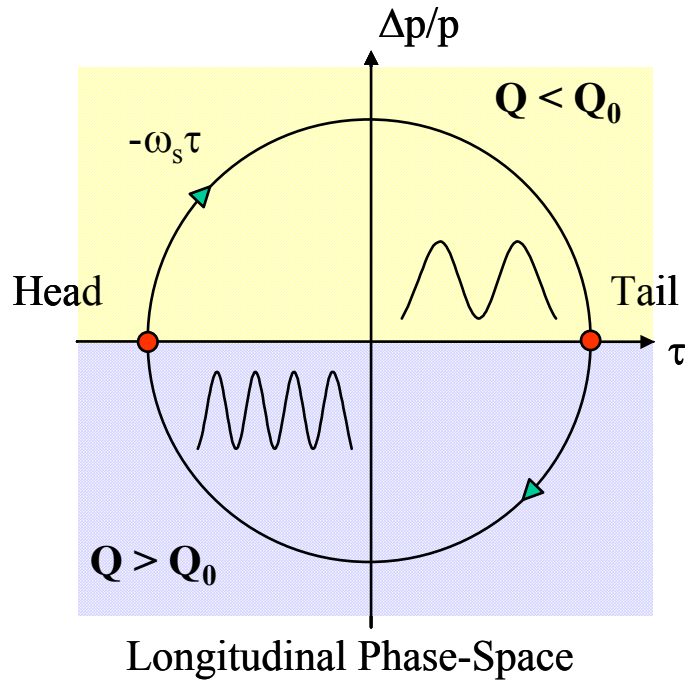# The Head-Tail Principle

- The Principle:
  - → Apply single transverse kick and observe resulting betatron motion.
  - → Chromaticity will determine the pattern of this motion.
  - → By following the time evolution of any two positions within the bunch a phase-difference is obtained from which the chromaticity can be calculated.
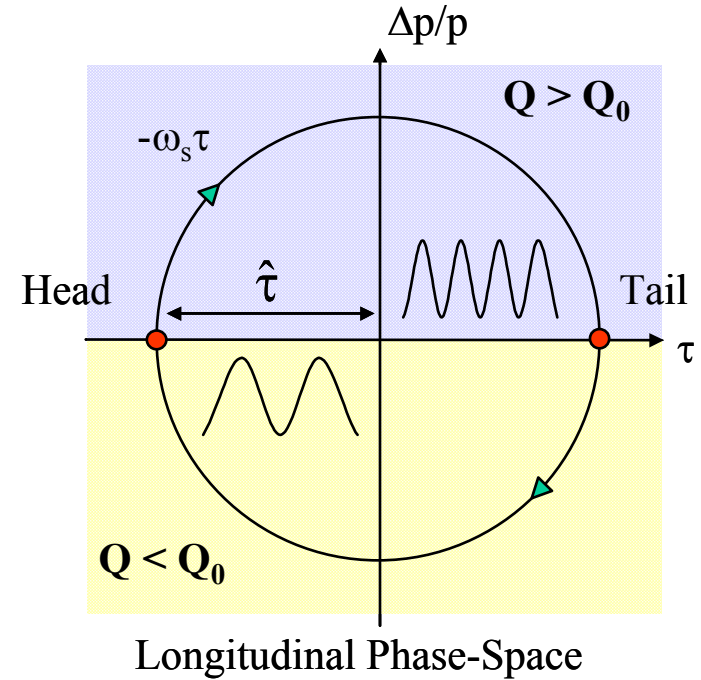
- Assumptions used in the Theory:
  - → The displacement due to the kick is much larger than the betatron oscillations performed by the particles in the unperturbed bunch.
    - i.e. when the kick is applied all particles are assumed to have the same betatron phase.
  - → The synchrotron frequency is the same for all particles in the bunch.
    - This assumption holds as long as the measurements are performed close to the centre of the bunch.
  - → The presence of higher order fields such as octupolar fields are not taken into consideration.

The Head-Tail Principle

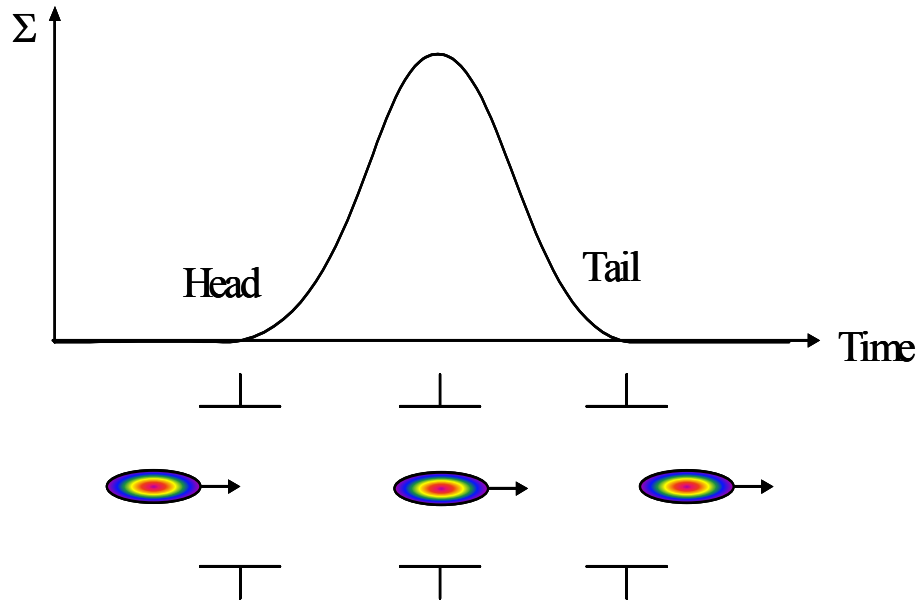Negative Chromaticity (Above Transition)

$\Delta p/p$

$Q < Q_0$

$-\omega_s\tau$

Head   Tail

τ

$Q > Q_0$

Longitudinal Phase-Space

Positive Chromaticity (Above Transition)

$\Delta p/p$

$Q > Q_0$

$-\omega_s\tau$

$\hat{\tau}$
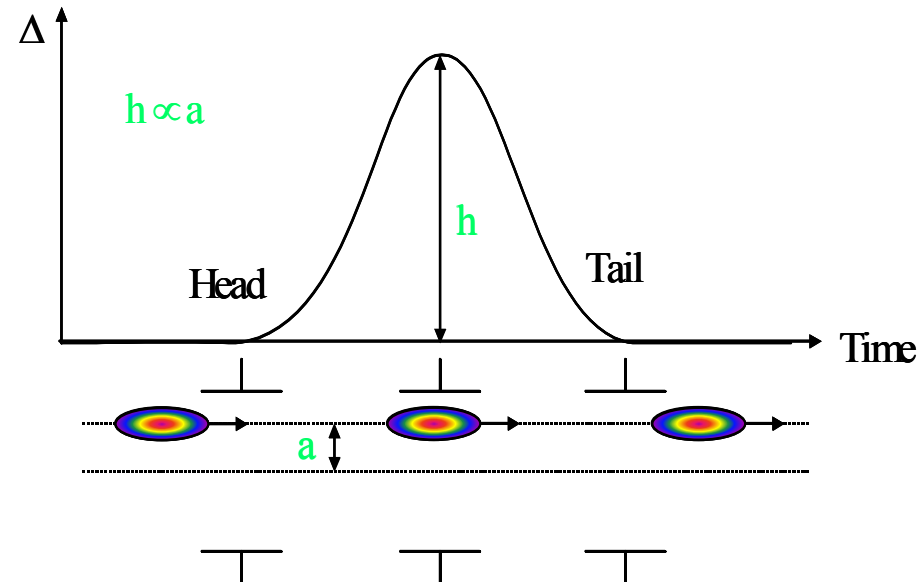
Head   Tail
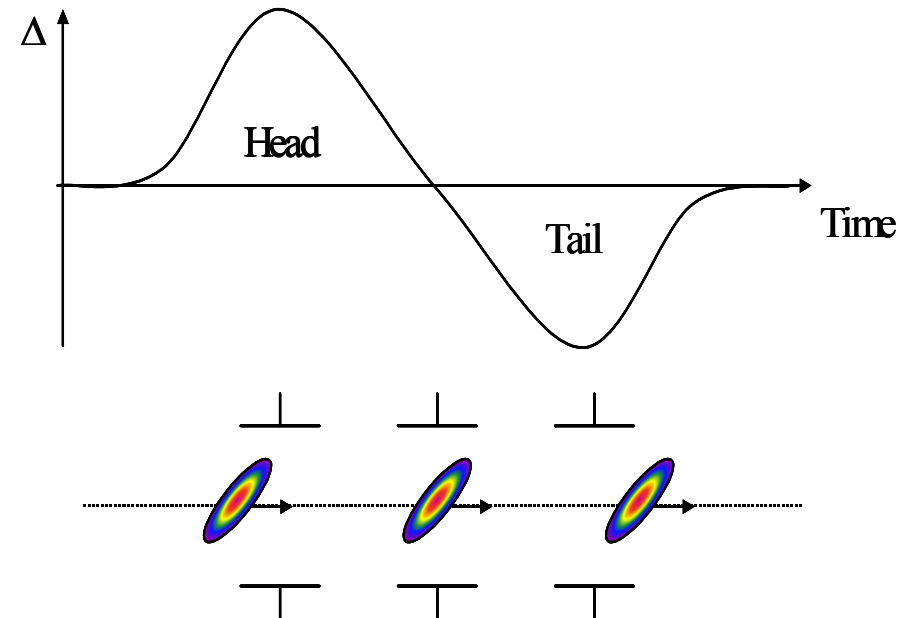
τ

$Q < Q_0$

Longitudinal Phase-Space

The Head-Tail Principle

Σ Signal - Longitudinal Bunch Profile

Response for
Zero Chromaticity

Δ Signal - Transverse Bunch Position

The Head-Tail Principle

Σ Signal - Longitudinal Bunch Profile

Σ

Head

Tail

Time
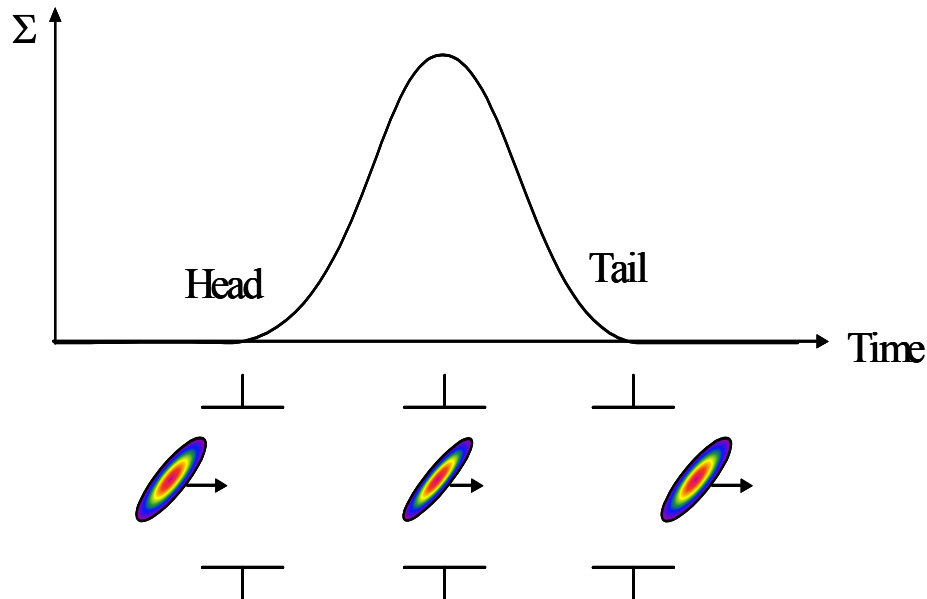
Response for
Non-Zero Chromaticity

Δ Signal - Transverse Bunch Position

Δ

Head

Tail

Time

The Head-Tail Principle

The phase difference as a function of the number of turns from an initial kick is given by

$$\Delta\psi(n) = -\omega_\xi \Delta\tau \left(\cos(2\pi n Q_s) - 1\right)$$

where ω_ξ is the chromatic frequency and is defined as $\omega_\xi = Q_0\,\omega_0\,\dfrac{\xi}{\eta}$

The maximum phase shift is obtained after half a synchrotron period, when $nQ_s = \frac{1}{2}$

$$\Delta\psi_{MAX} = -2\omega_\xi\,\Delta\tau$$

The relative chromaticity can therefore be written as

$$\xi = \frac{-\eta\,\Delta\psi(n)}{Q_0\,\omega_0\Delta\tau\left(\cos(2\pi n Q_s) - 1\right)} = \frac{\eta\,\Delta\psi_{MAX}}{2\,Q_0\,\omega_0\,\Delta\tau}$$

ξ	=	relative chromaticity	$\Delta\psi$ =	head-tail phase difference
η	=	$1/(\gamma)^2 - \alpha$	$\Delta\tau$ =	time between the sampling of head and tail
Q_s	=	synchrotron tune	Q_0 =	betatron tune
ω_0	=	angular revolution frequency	n =	number of turns since the initial kick

CERN-SPS System Set-up

SPS Tunnel

Fast (2GS/s per channel)
Digital Oscilloscope

Straight
Stripline
Coupler

Hybrid

Sum

Difference

Beam

Beam Pipe

Bunch Synchronous
Trigger
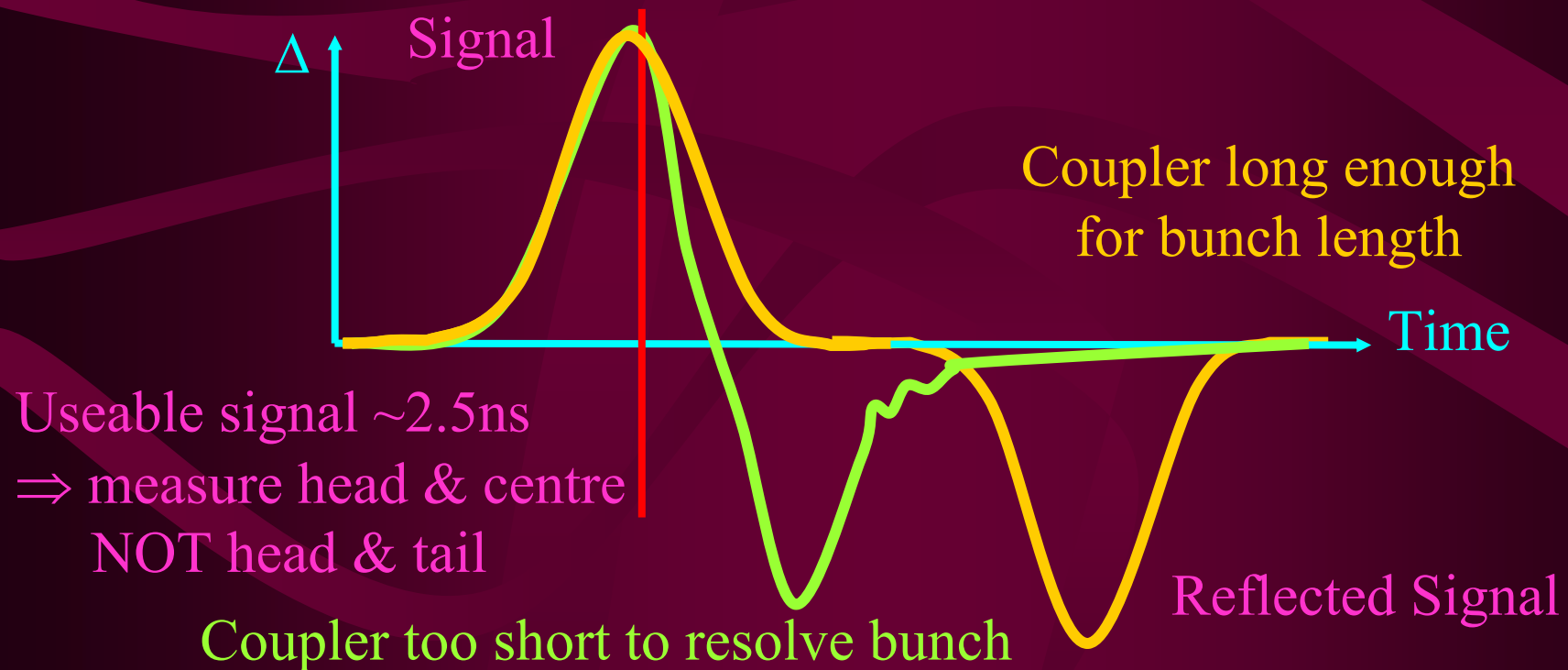
VME
Acquisition
via GPIB

UNIX
User Interface

GPIB link
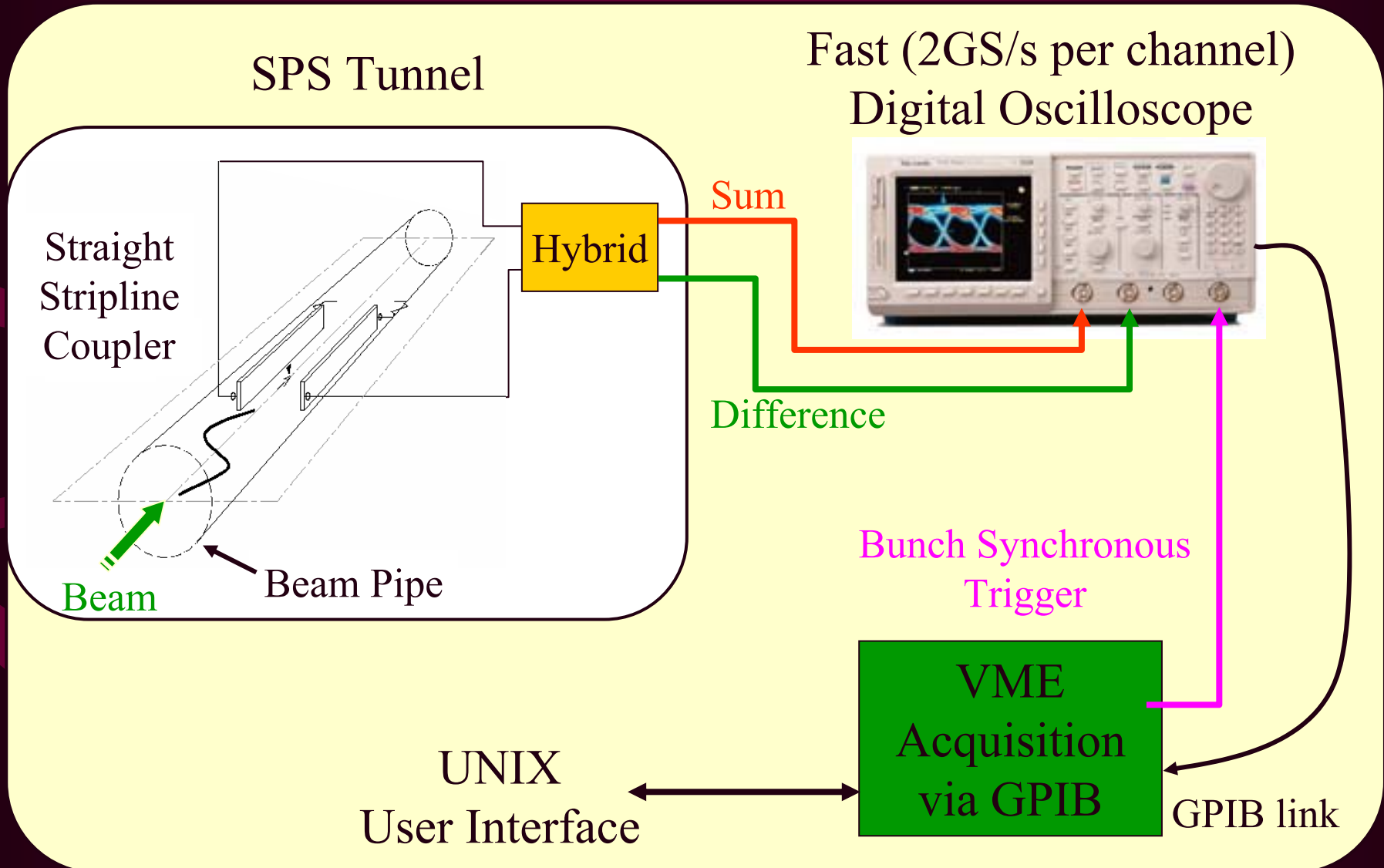
The CERN-SPS Head-Tail Monitor

Pick-up

- Straight stripline coupler - 37cm long

  → completely resolves a bunch < 2.5ns in length

  NOT the case in the CERN-SPS where bunch length is ~4ns

Δ   Signal

Coupler long enough
for bunch length

Time

Useable signal ~2.5ns
⇒ measure head & centre
NOT head & tail

Coupler too short to resolve bunch

Reflected Signal

Measurements Conditions

- Measurements performed during CERN-SPS "25ns Run"
  - $\rightarrow$ LHC batch of 84 bunches with 25ns bunch spacing
  - $\rightarrow$ Acceleration from 26GeV to 450GeV
  - $\rightarrow$ Intensity of $\sim 2\times10^{10}$ protons per bunch

- Q' measured mainly in the vertical plane
  - $\rightarrow$ Transverse Damper switched OFF in measurement plane
  - $\rightarrow$ Beam excited using a single kick from the Q-kickers

Measuring Q'
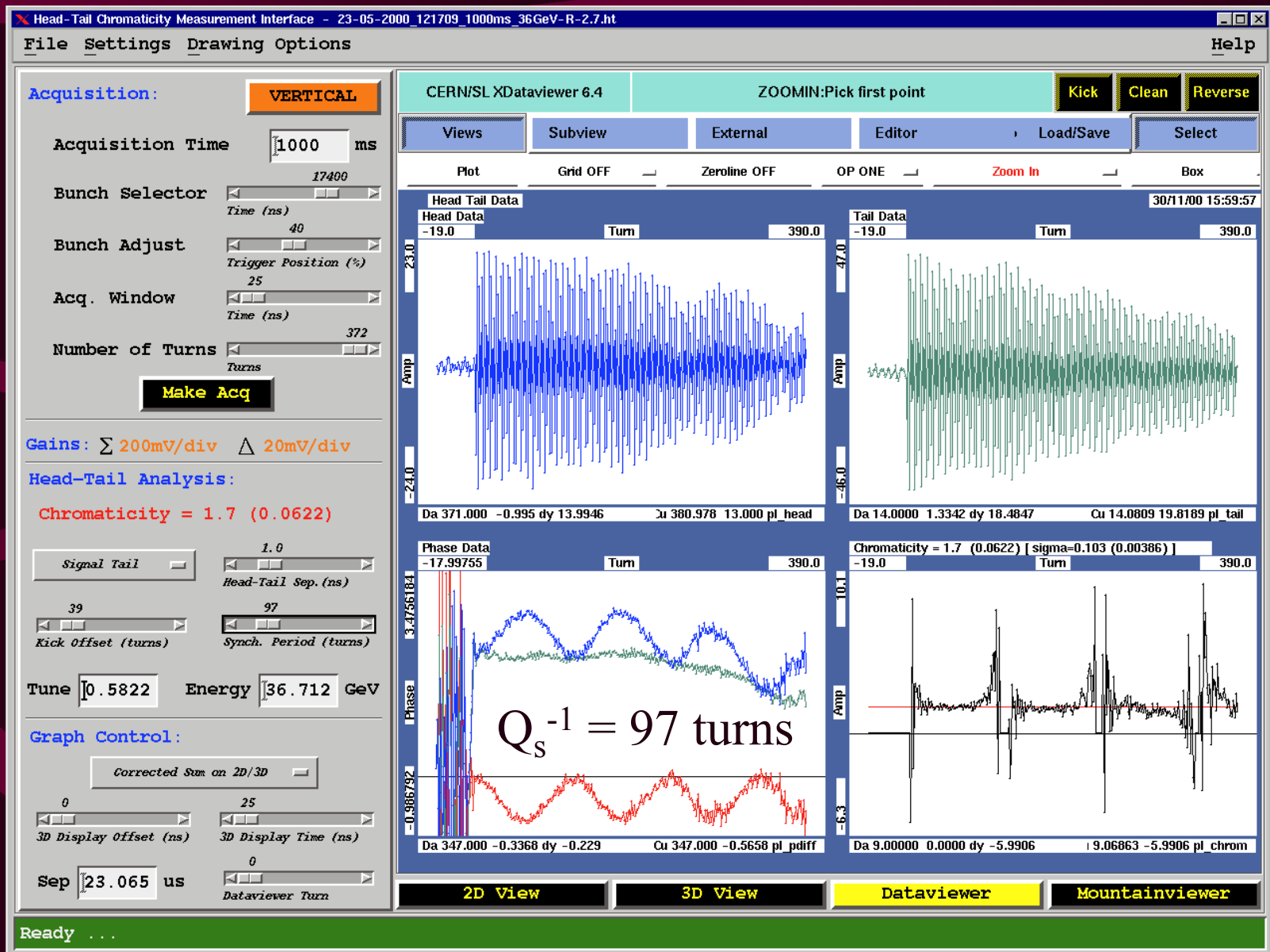
Measuring Q'
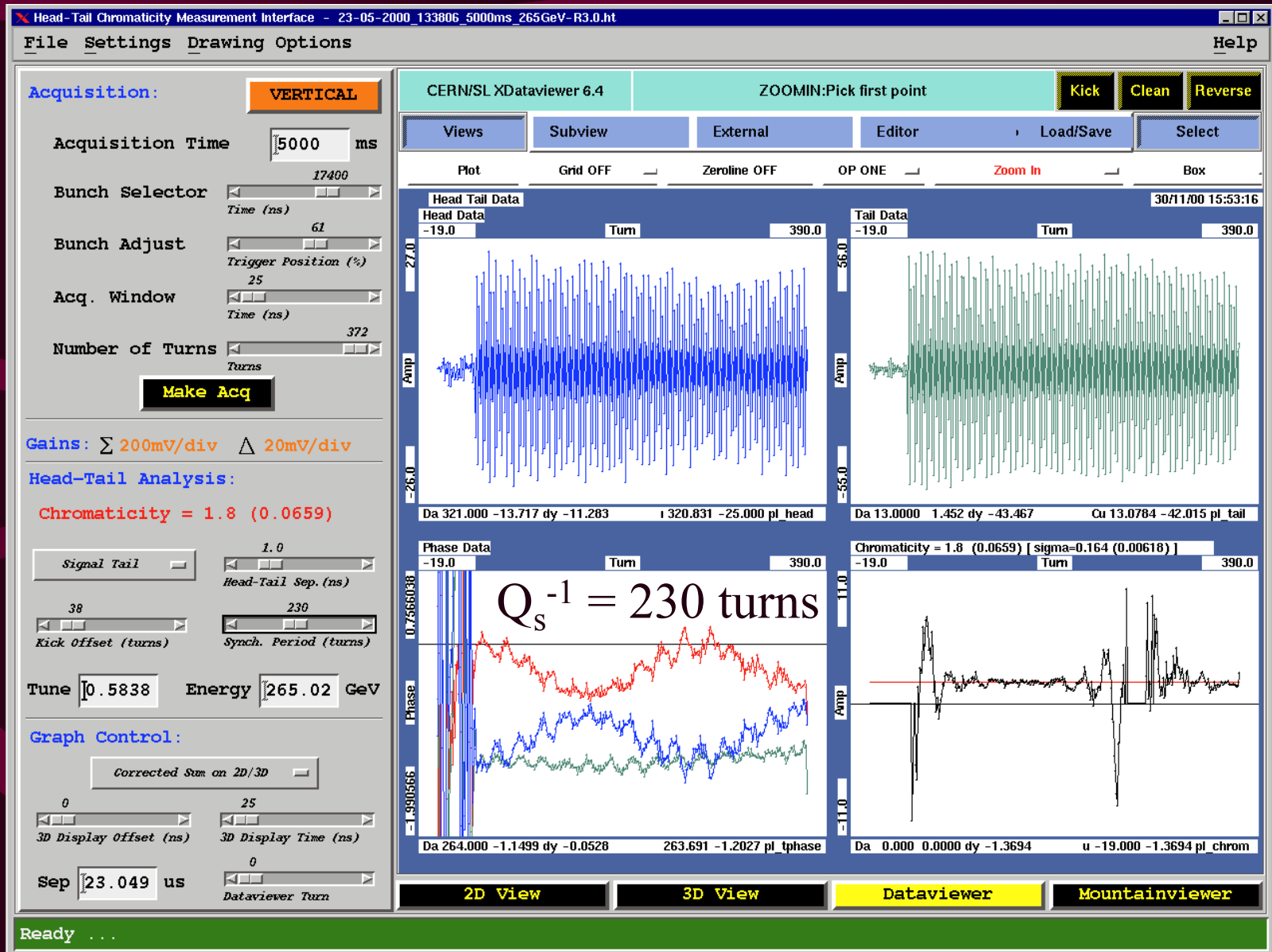
Measuring Q'

Comparison of Head-Tail Chromaticity Measurements
with Radial Steering Measurements at 115GeV in the SPS

$\xi_{head-tail} = 0.45\xi_{radial-steering}$ + orbit dependent offset

Scaling factor of 2.2 (=0.45^{-1}) at 115GeV

Legend:
- -2.1mm Orbit
- +0.1mm Orbit
- +2.6mm Orbit

X-axis: Radial Steering Chromaticity (ξ)
Y-axis: Head-Tail Chromaticity (ξ)
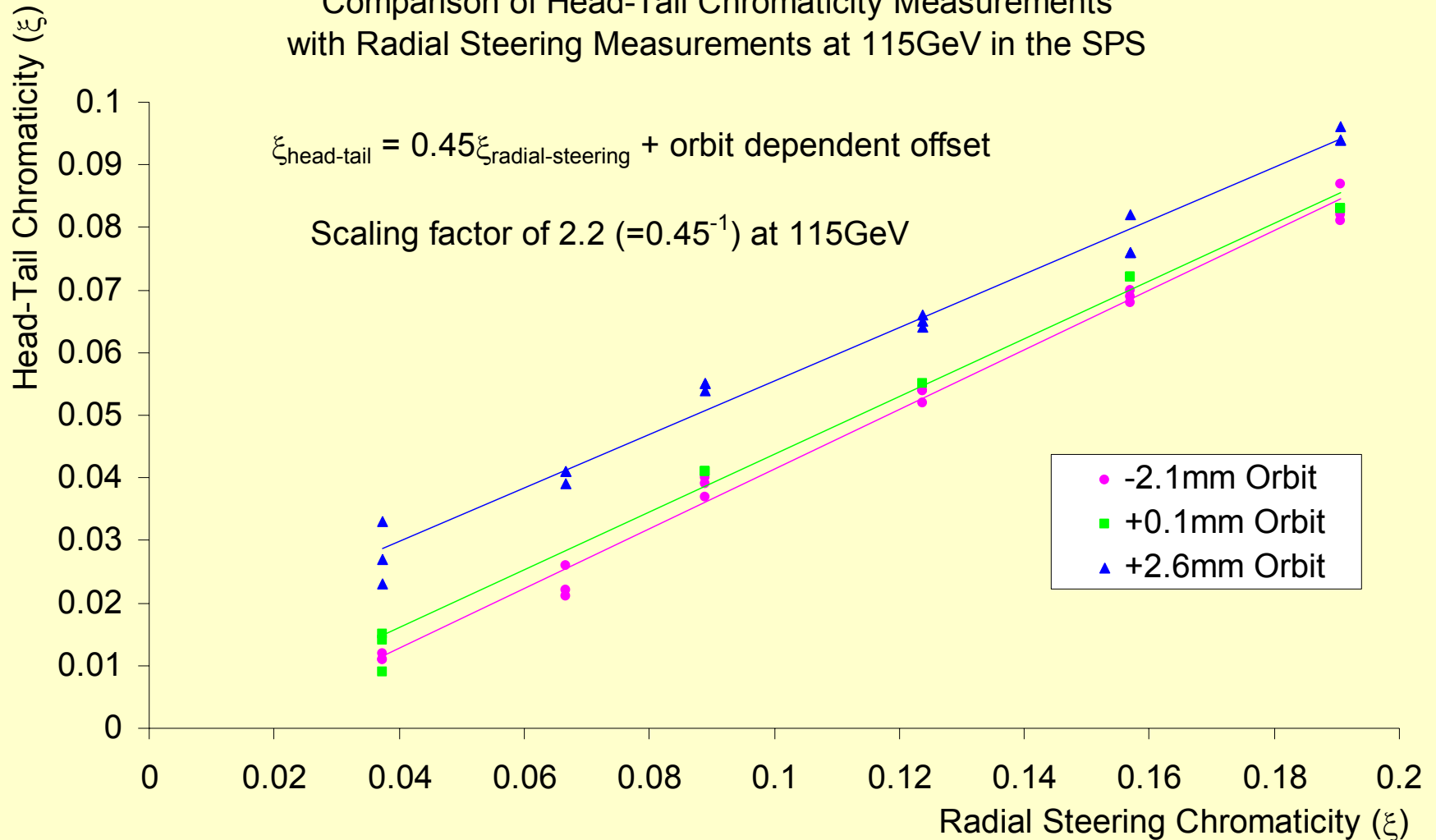
Measuring Q'' and Q'''

Radial Position versus Chromaticity (115GeV)

- Radial Steering
- Scaled Head-Tail
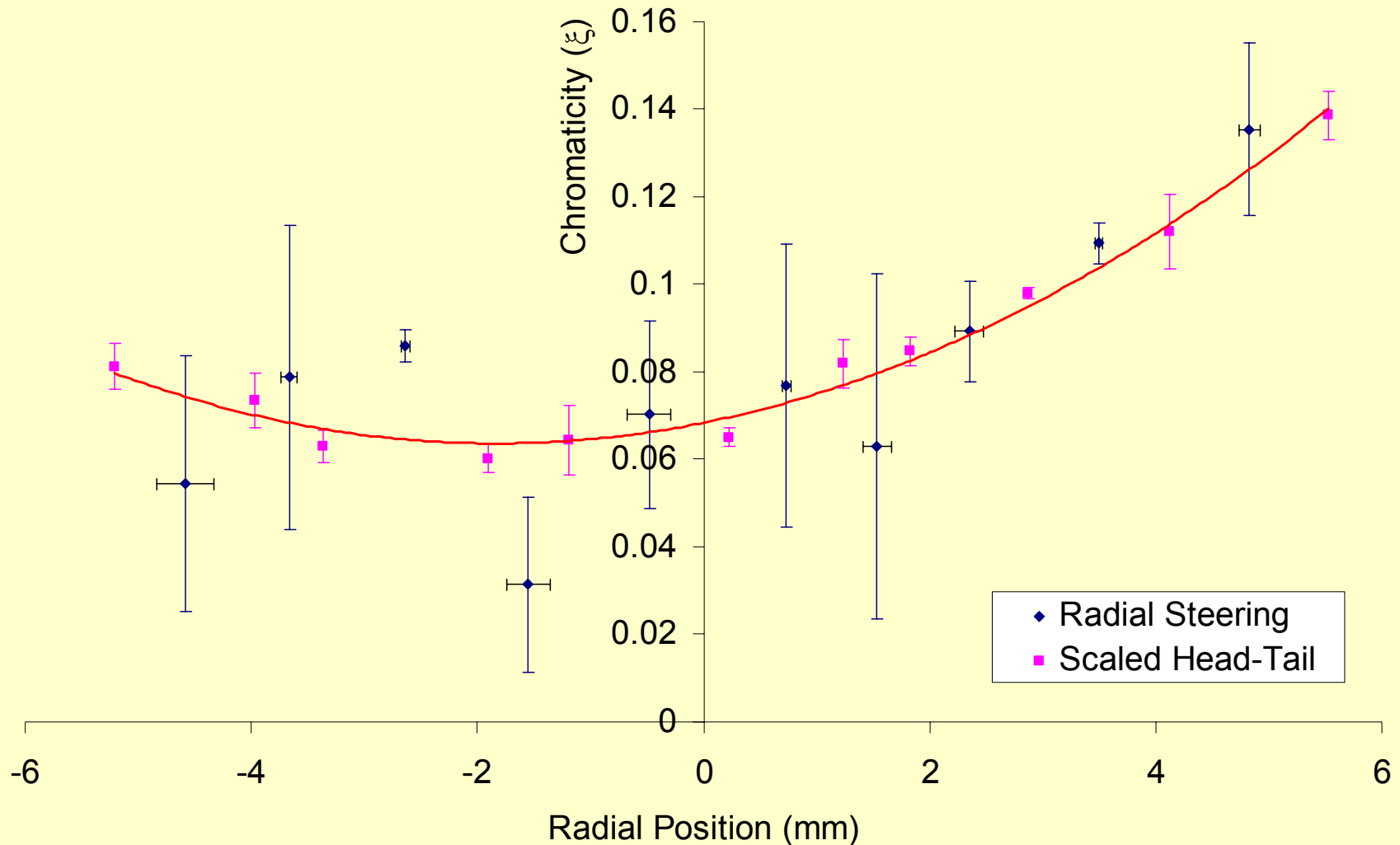
Multiple Q' Measurements

- Several Q' Measurements on SAME SPS elementary cycle
  - → rate limited to 0.5Hz by GPIB data transfer & scope reset time
  - → demonstrated on SPS using 3 Q-kickers

1000ms : 36GeV   3000ms : 115GeV   5000ms : 265GeV
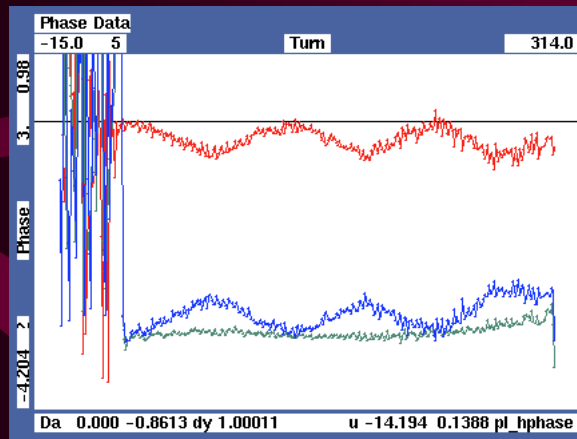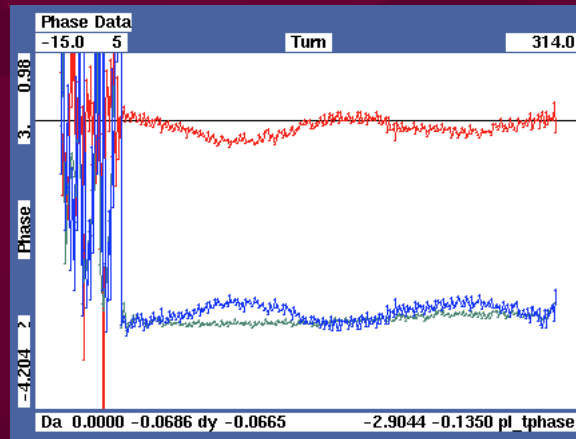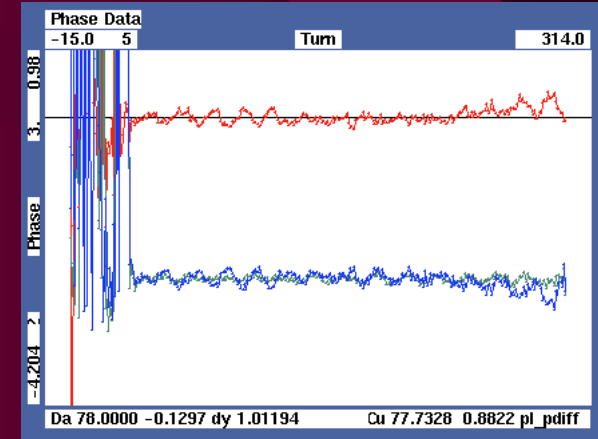
ξ=0.036 ξ=0.037 ξ=0.005

Improvements and Developments in 2001/2002

- Added 60cm long coupler
  - → can fully resolve bunches up to 4ns in length
- Added low loss cables & reduced cable length
  - → increase in the overall system bandwidth
- Performed more complete simulations
  - → originally intended to find source of missing factor
    - Turned out to be hardware related
  - → developed into a robustness study for the technique
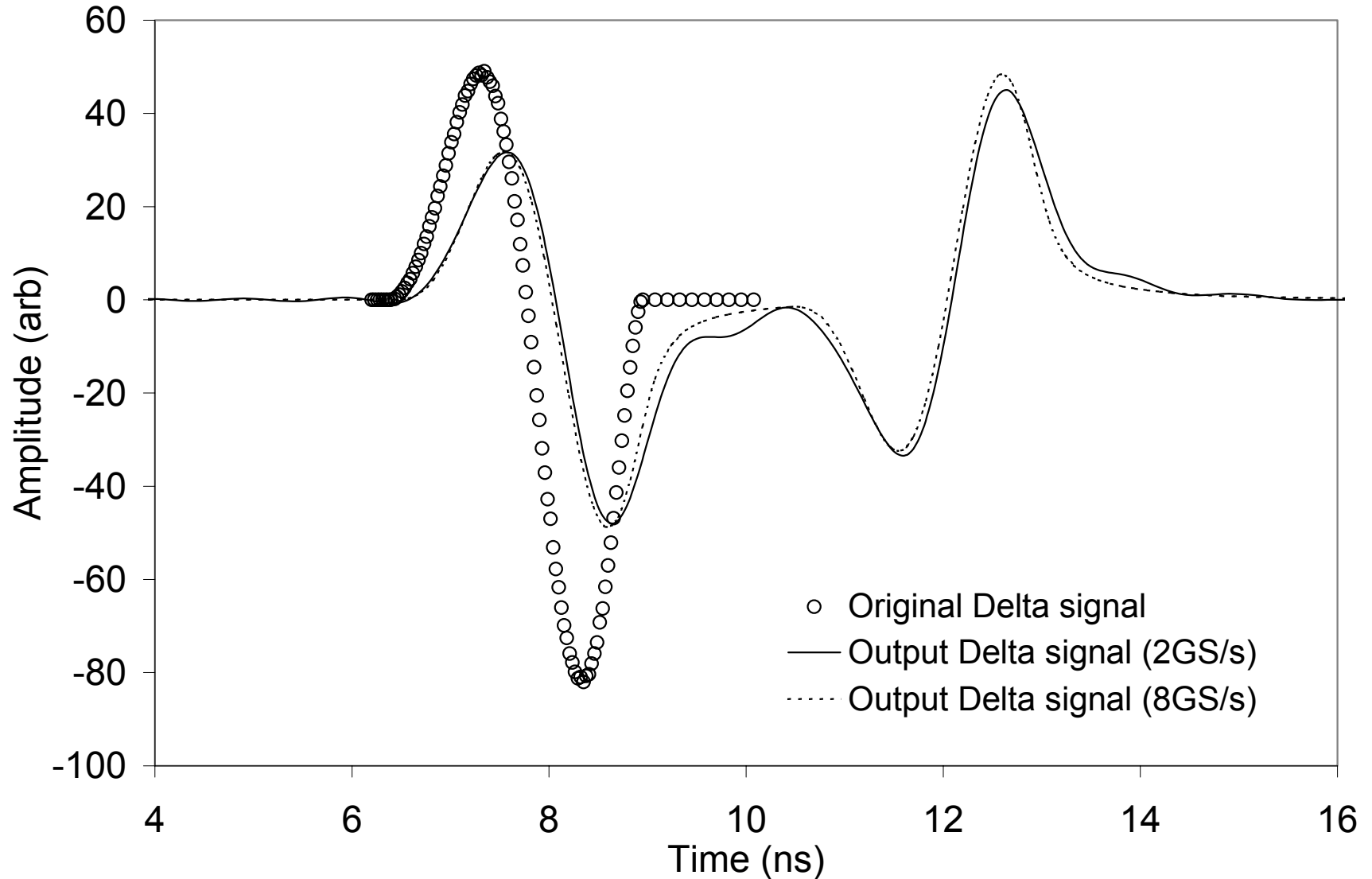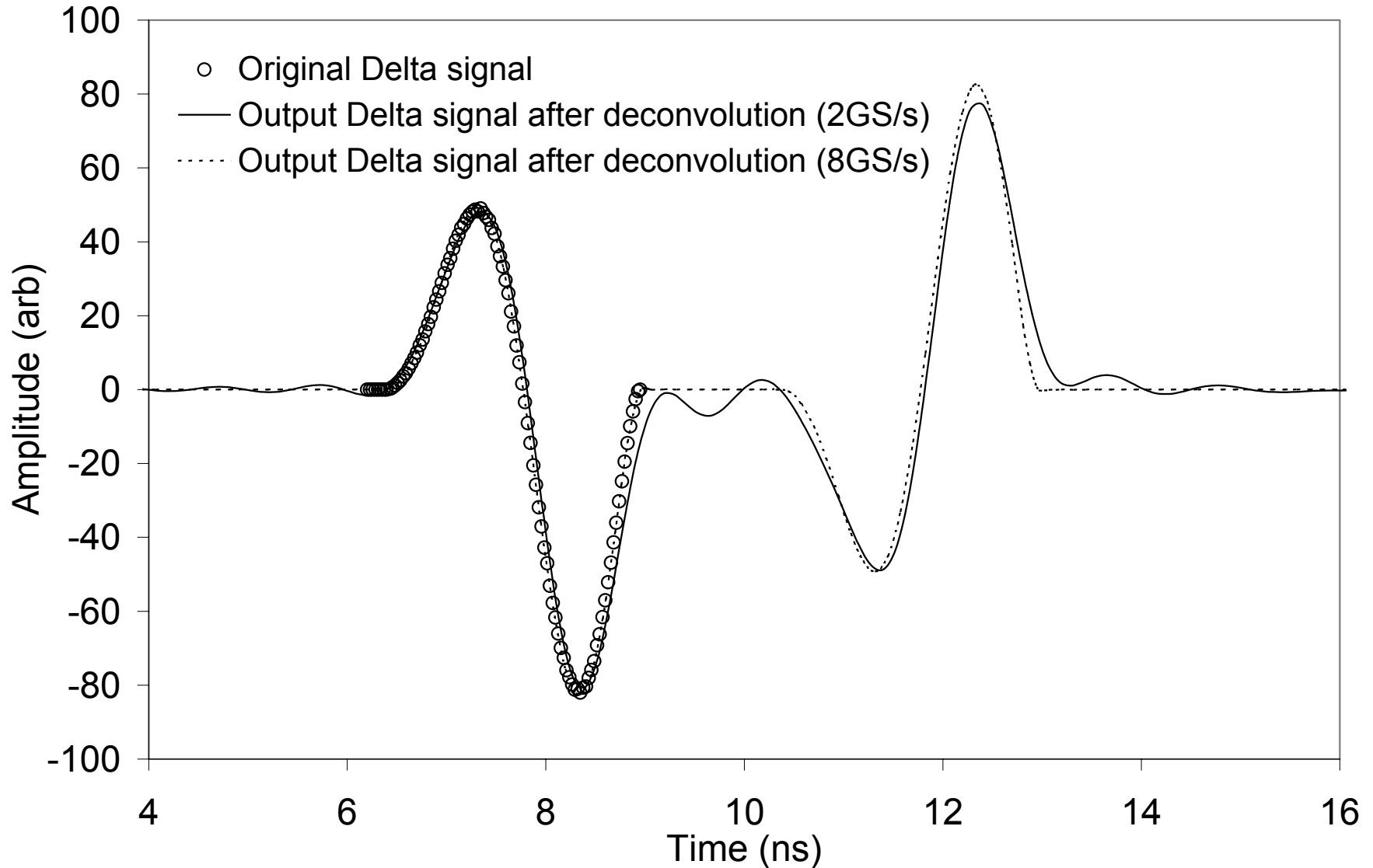   - Effect of accelerating buckets
    - Effect of Q'' and Q'''

Measuring Q' (long coupler)
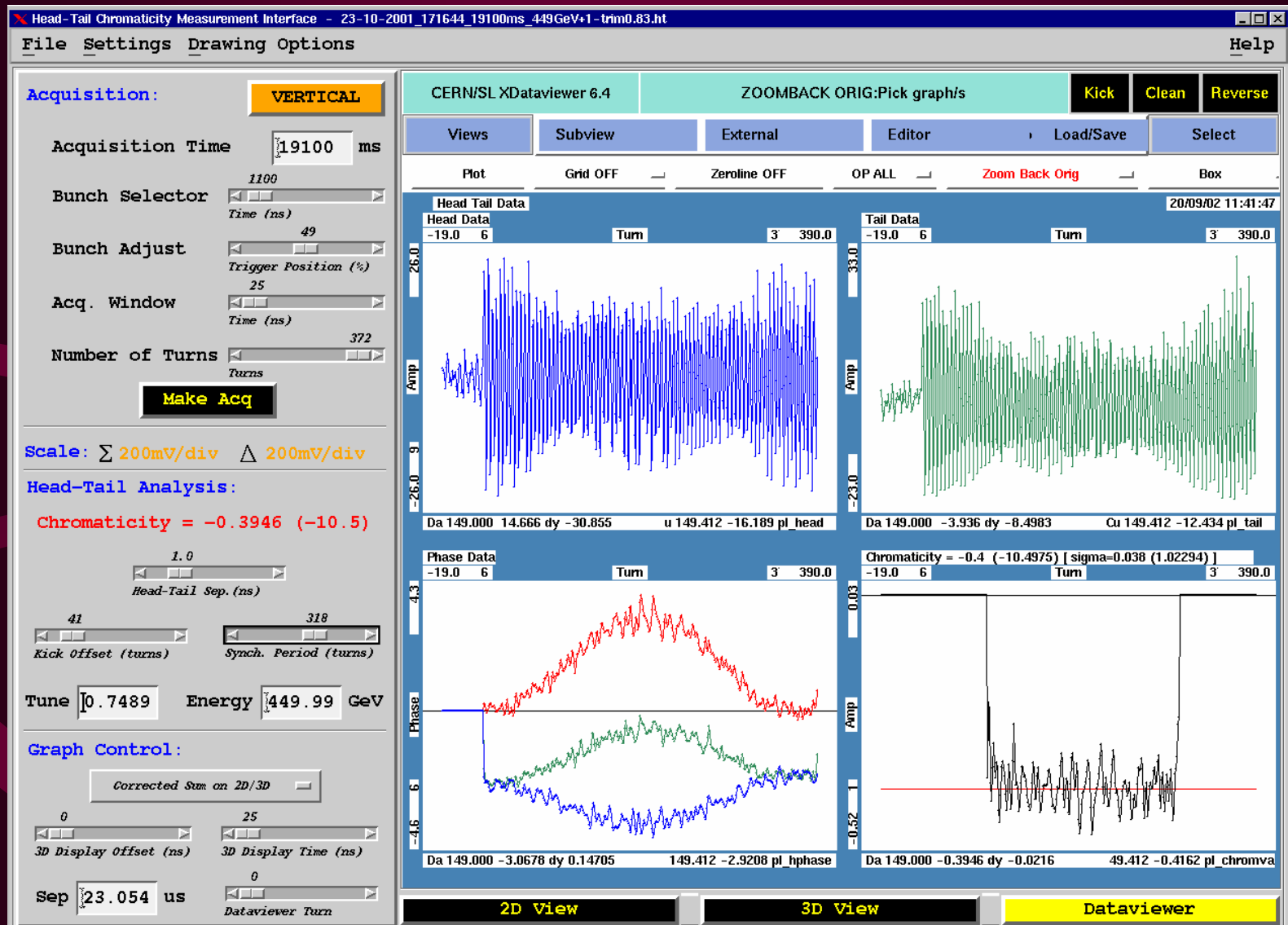
Understanding the Scaling Factor

Factor down from 2.2 to 1.4
From 2000 to 2001

Legend:
- ▲ Radial steering chromaticity
- ● Raw head-tail chromaticity
- ⋯ Head-Tail results x 1.4

X-axis: Sextupole Trim Value
Y-axis: Measured Chromaticity
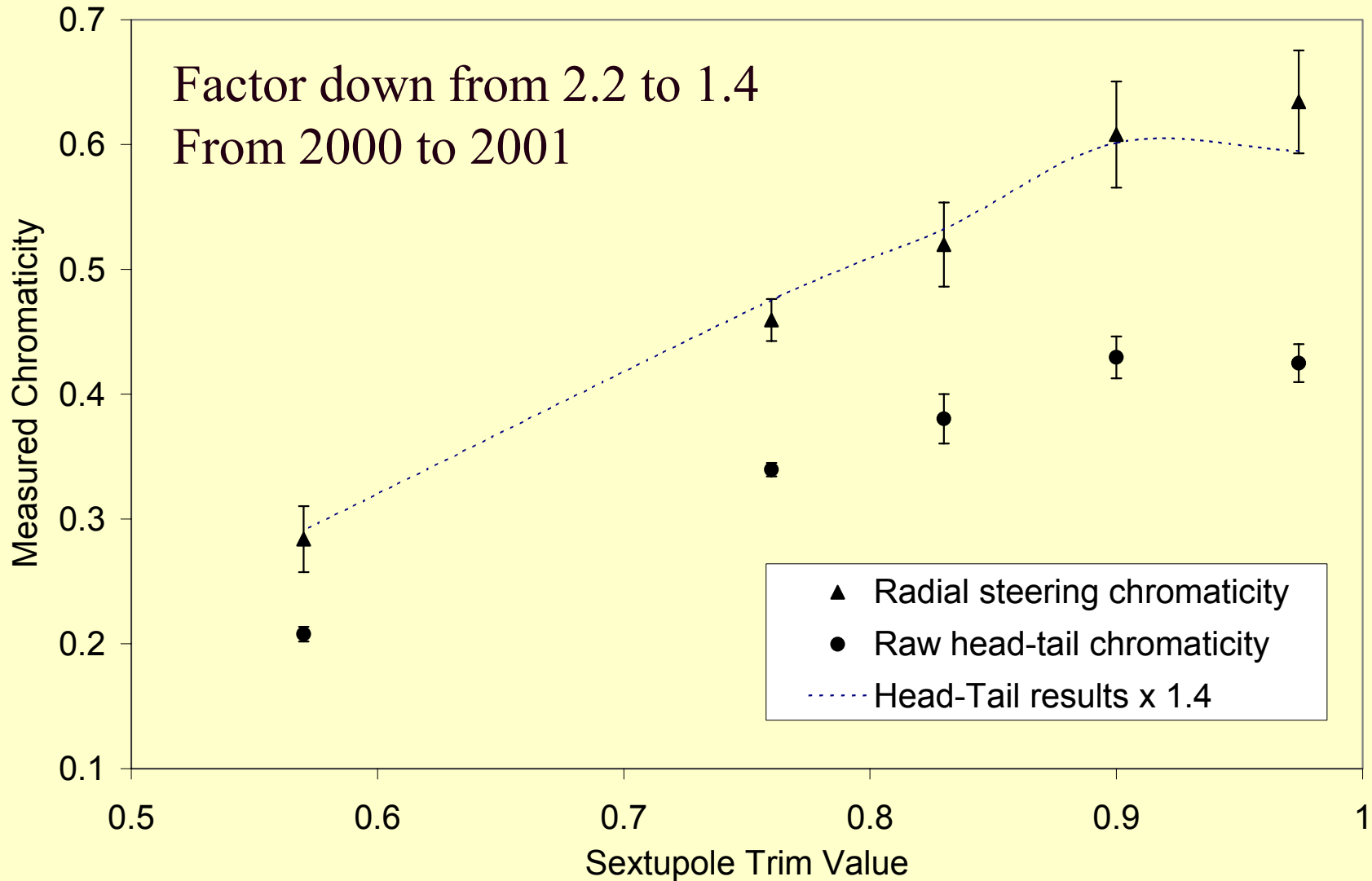
Signal Output

Signal Output

Effect of Deconvolving Cable Response

Real CERN-SPS Data

Correction Factor vs Chromaticity

▲ Raw 2GS/s Head-Tail Data
○ Deconvoluted 2GS/s Head-Tail Data (cable only)
● Deconvoluted 2GS/s Head-Tail Data (cable + scope)
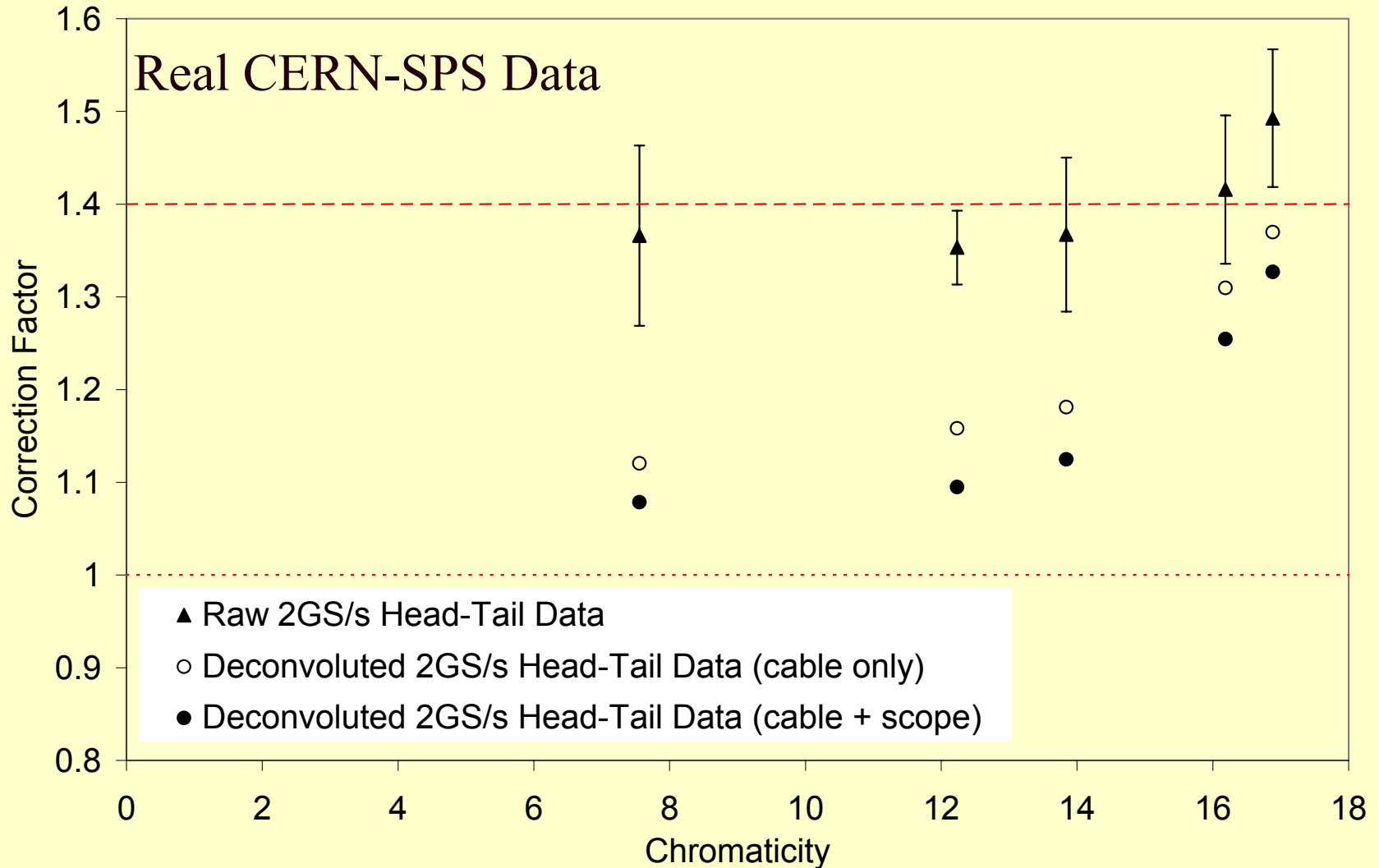
Effect of Sampling Rate
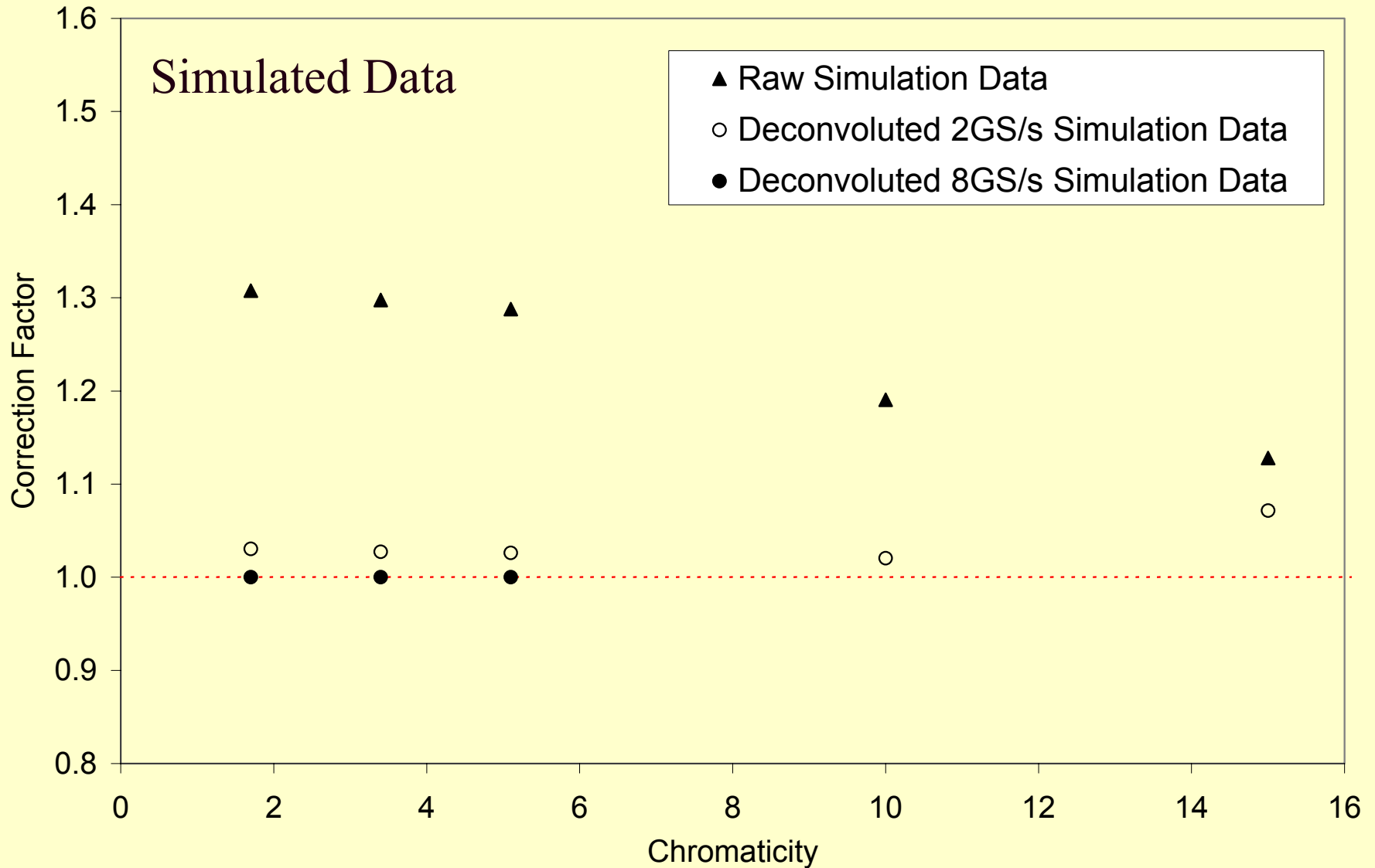
Simulations
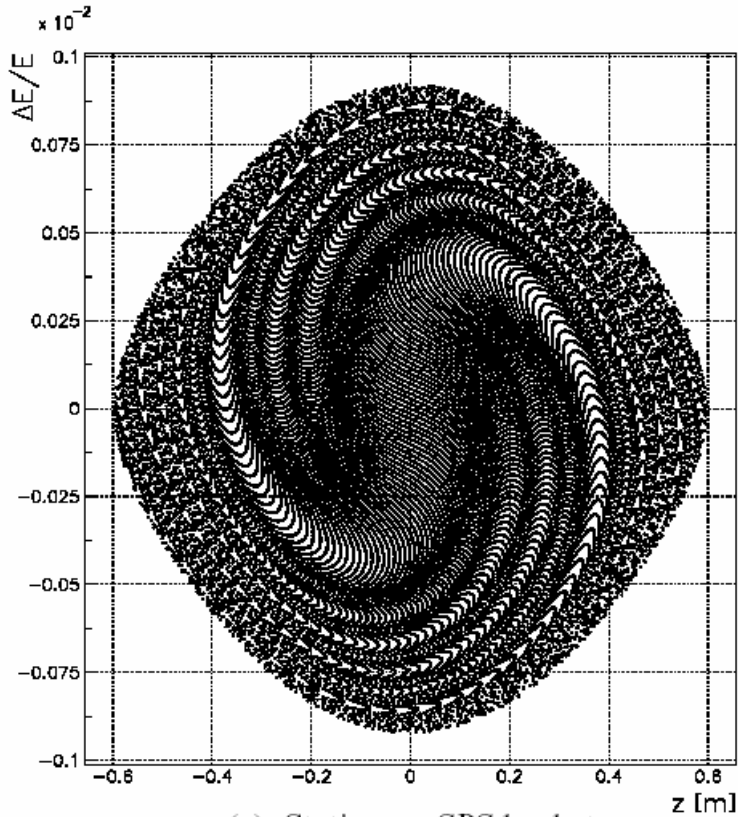
(a): Stationary SPS bucket
at 303.91 GeV ($V_{\mathrm{RF}} = 3.87$ MV, $\phi_s = 0$)
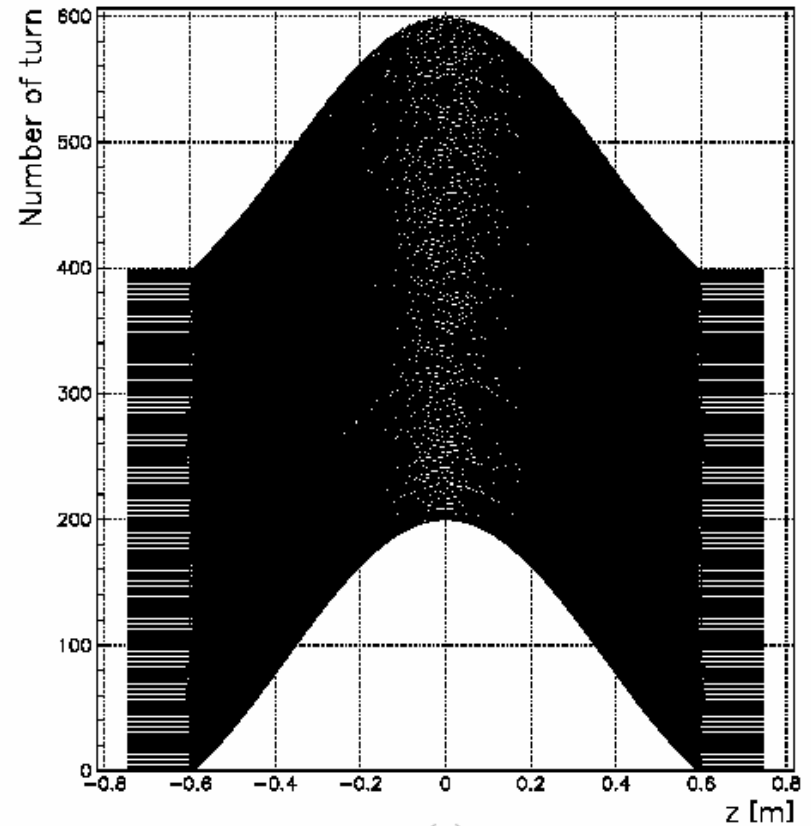
(c)

Simulations
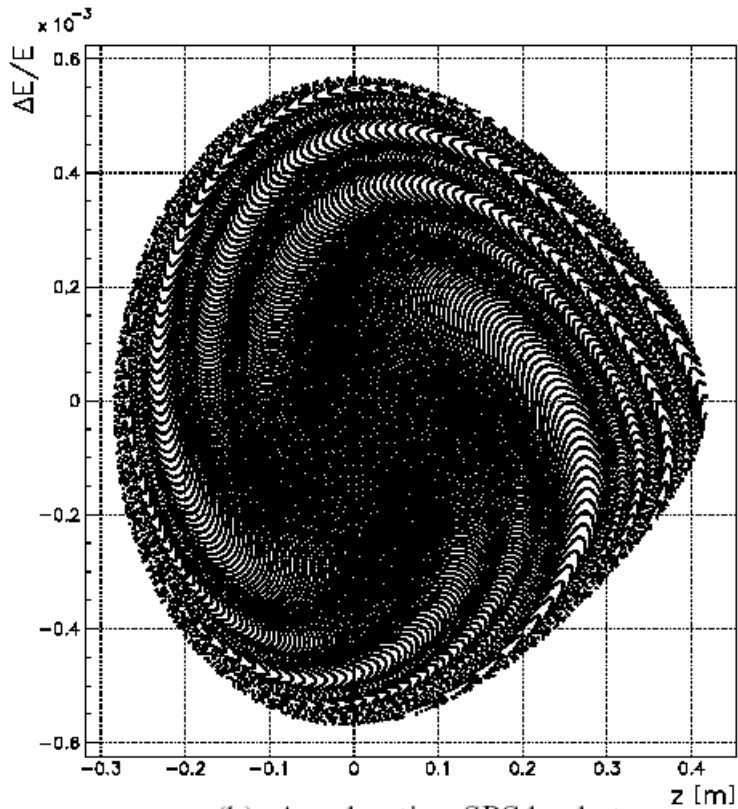
(b): Accelerating SPS bucket
at 303.91 GeV ($V_{RF} = 3.87$ MV, $\phi_s = 27.7°$)
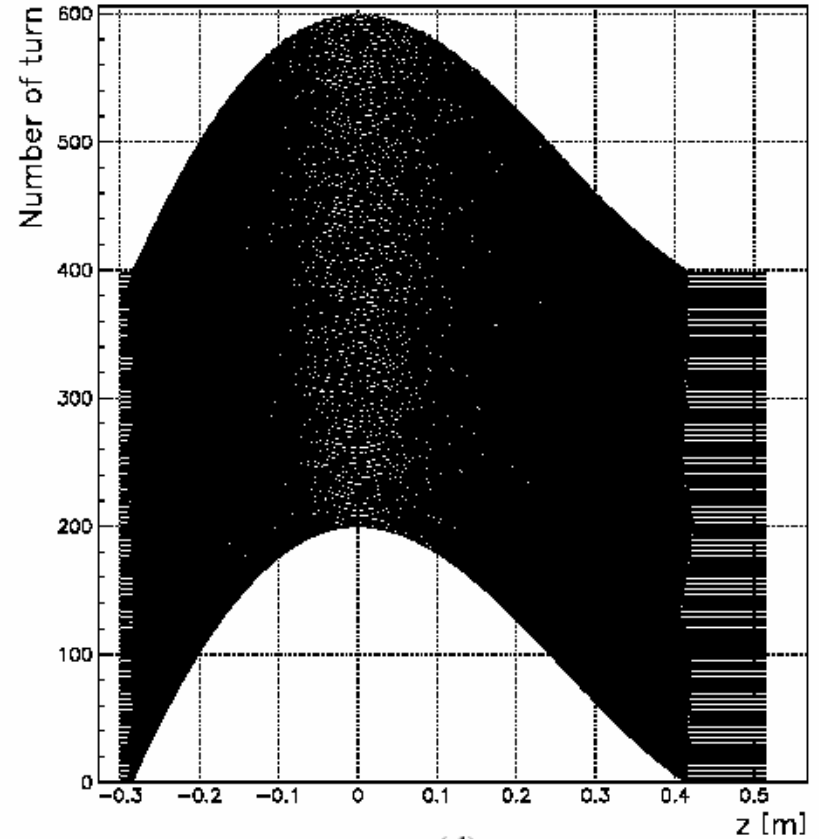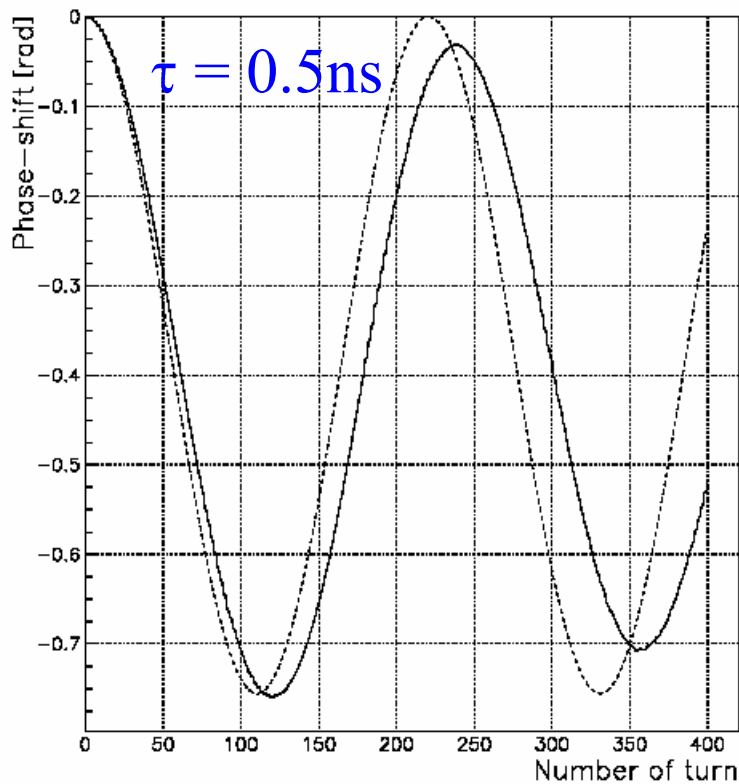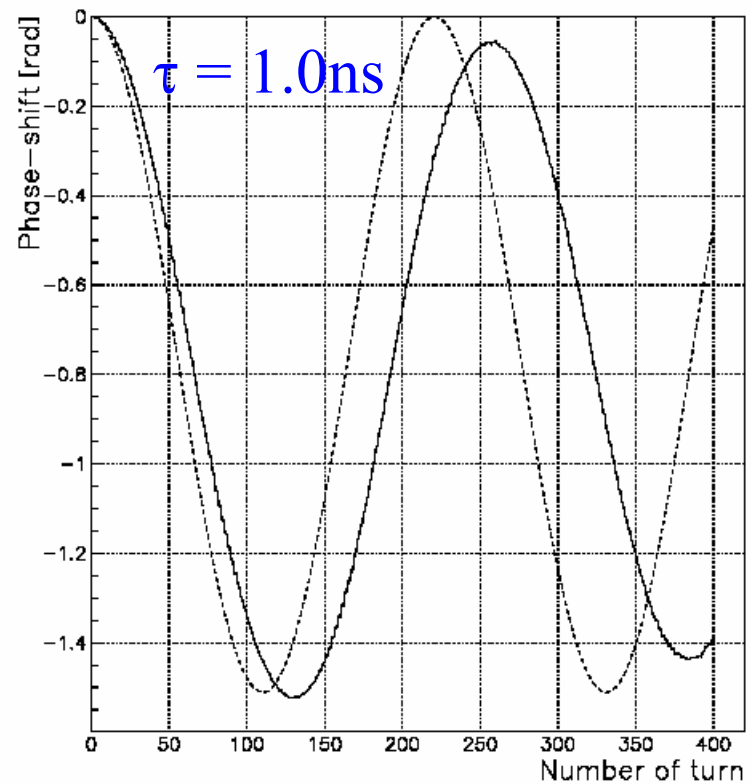

(d)

Tracking v Analytical Approach

Stationary Bucket:

- Measurement at Bunch Head w.r.t. Bunch Centre
- Comparison of tracking (solid lines) & analytical estimate (dashed)
- Error in ϕ_{MAX} negligible

$\tau = 0.5ns$

$\tau = 1.0ns$

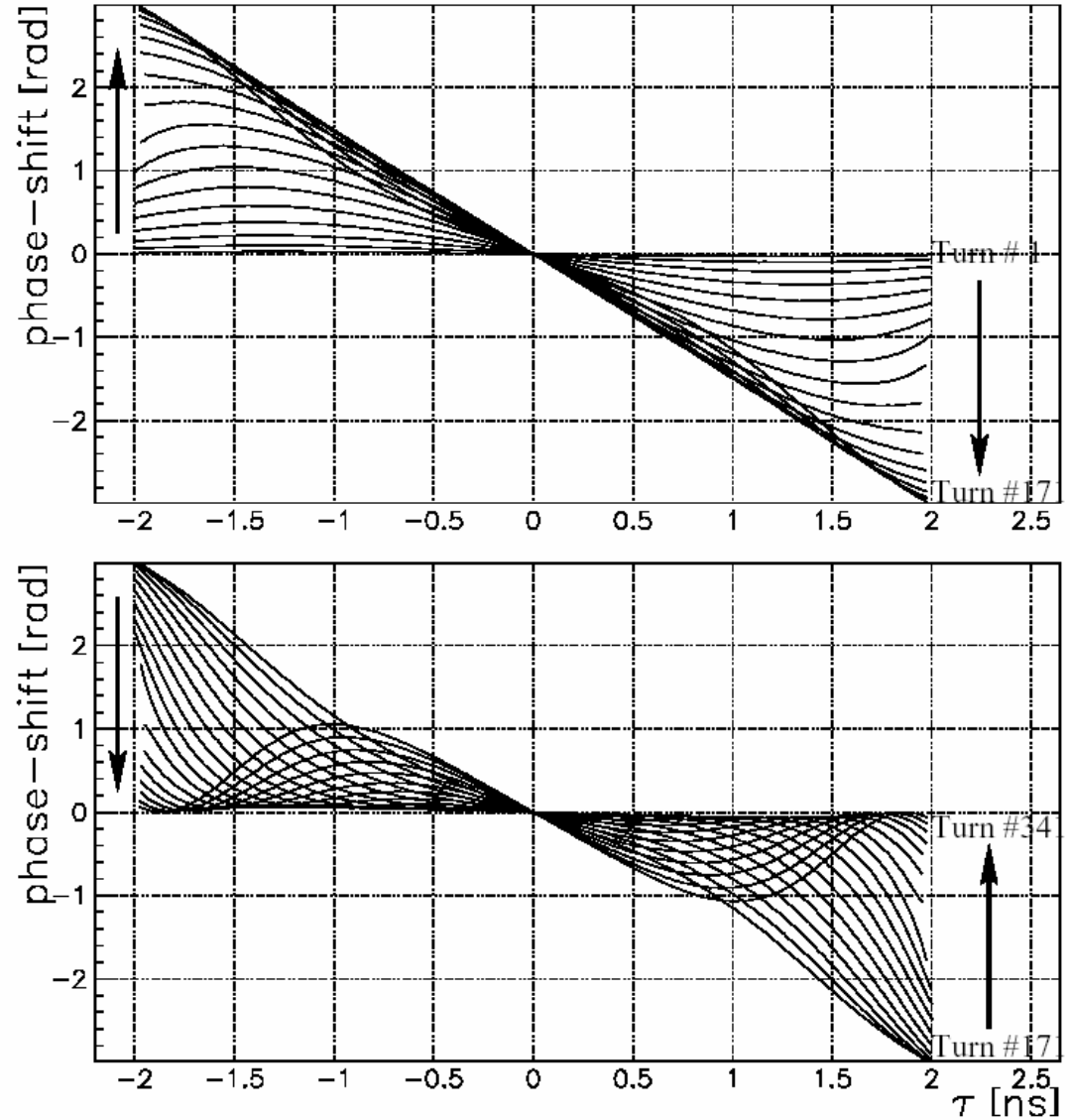(e): Betatron phase-shift [rad]

(f): Betatron phase-shift [rad]

Tracking Results

Stationary Bucket:
- Maximum phase shift reached is linear with distance from centre
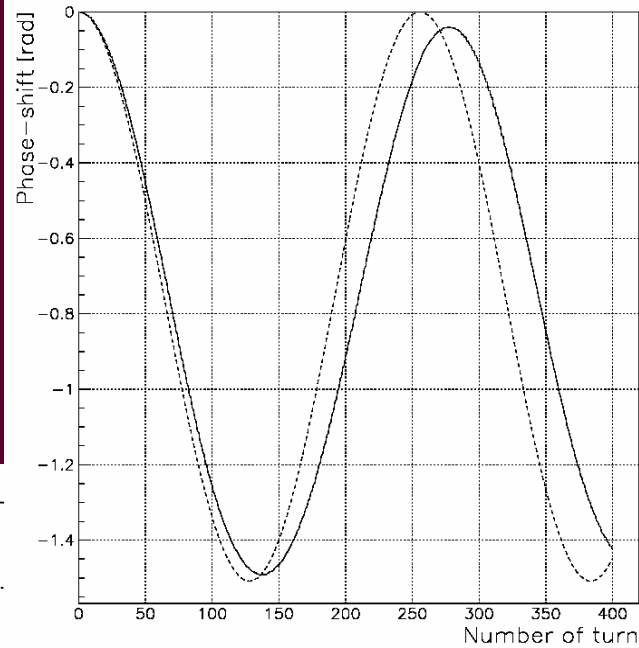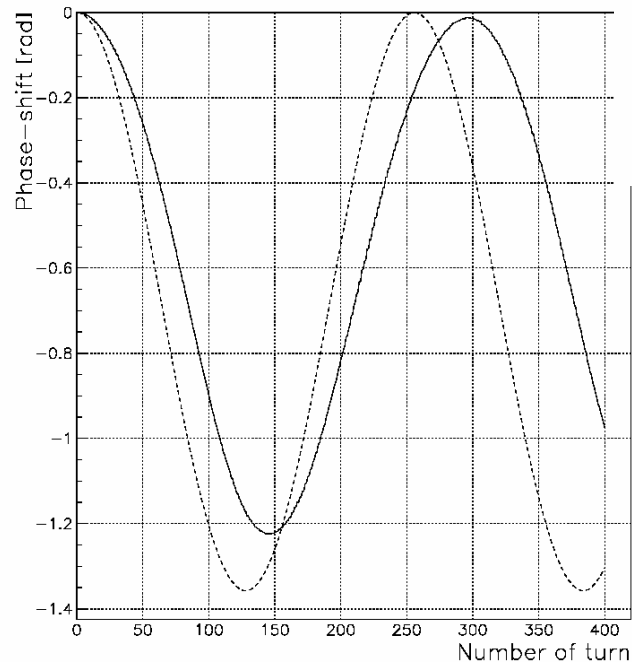
Measurement is valid for:
- Centre to Head
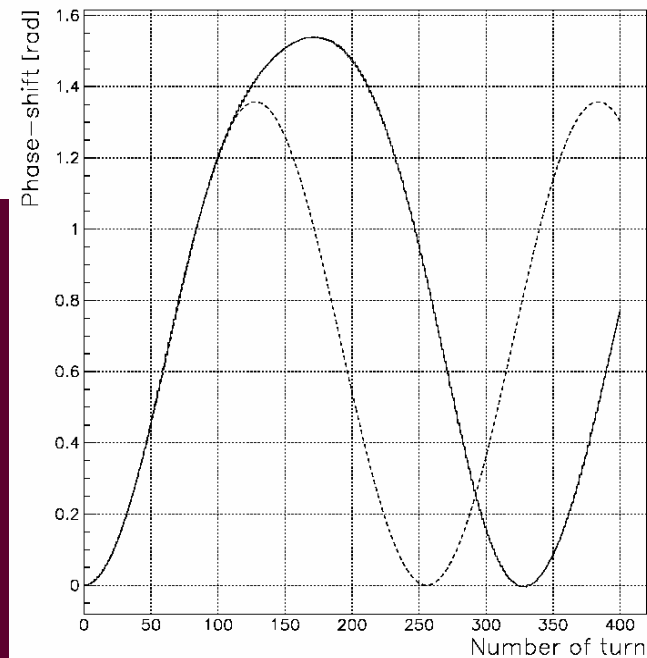- Centre to Tail
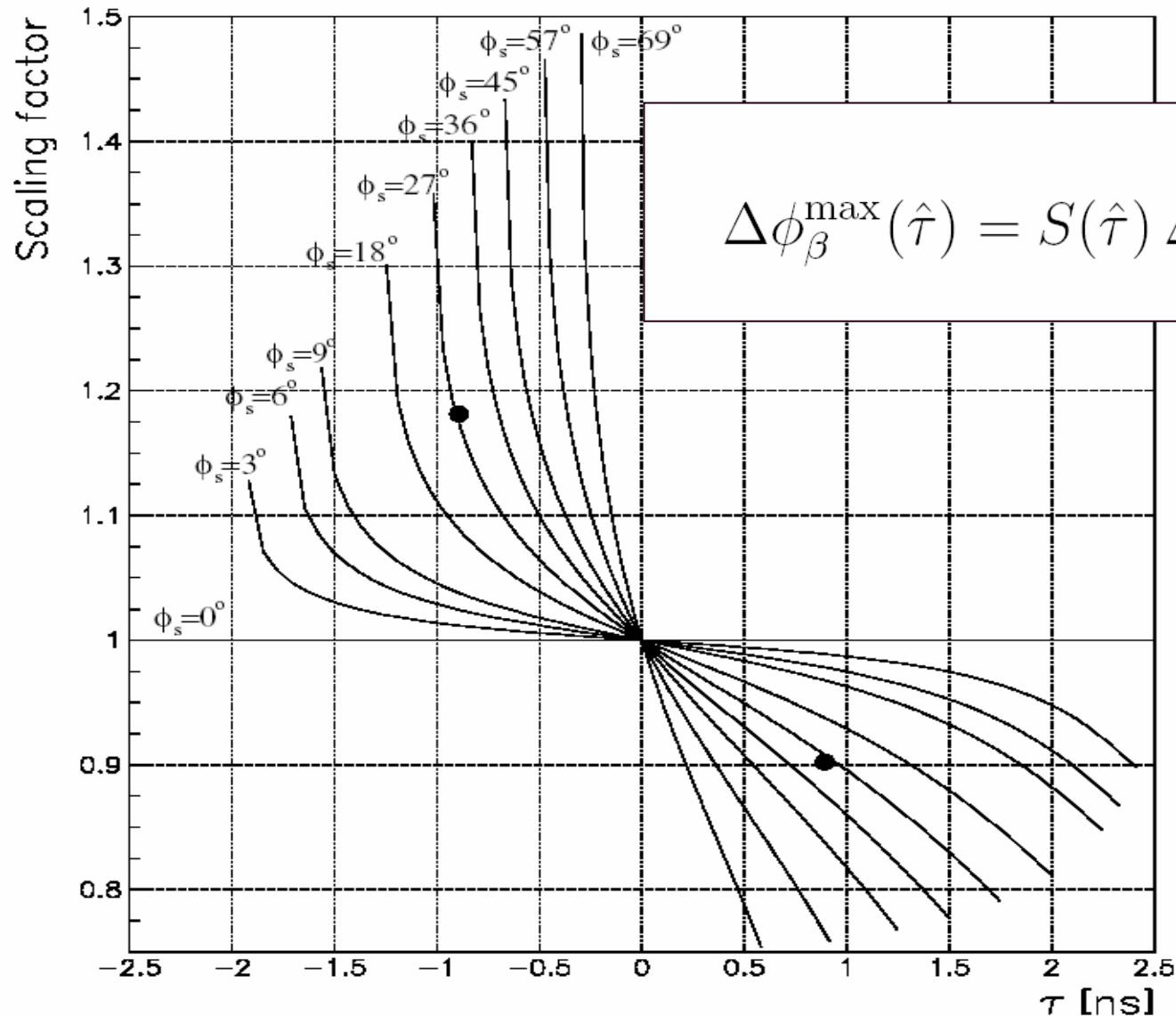- Symmetric Head to Tail

Effect of Acceleration

Head & Centre

Centre & Tail

Symmetric
Head & Tail

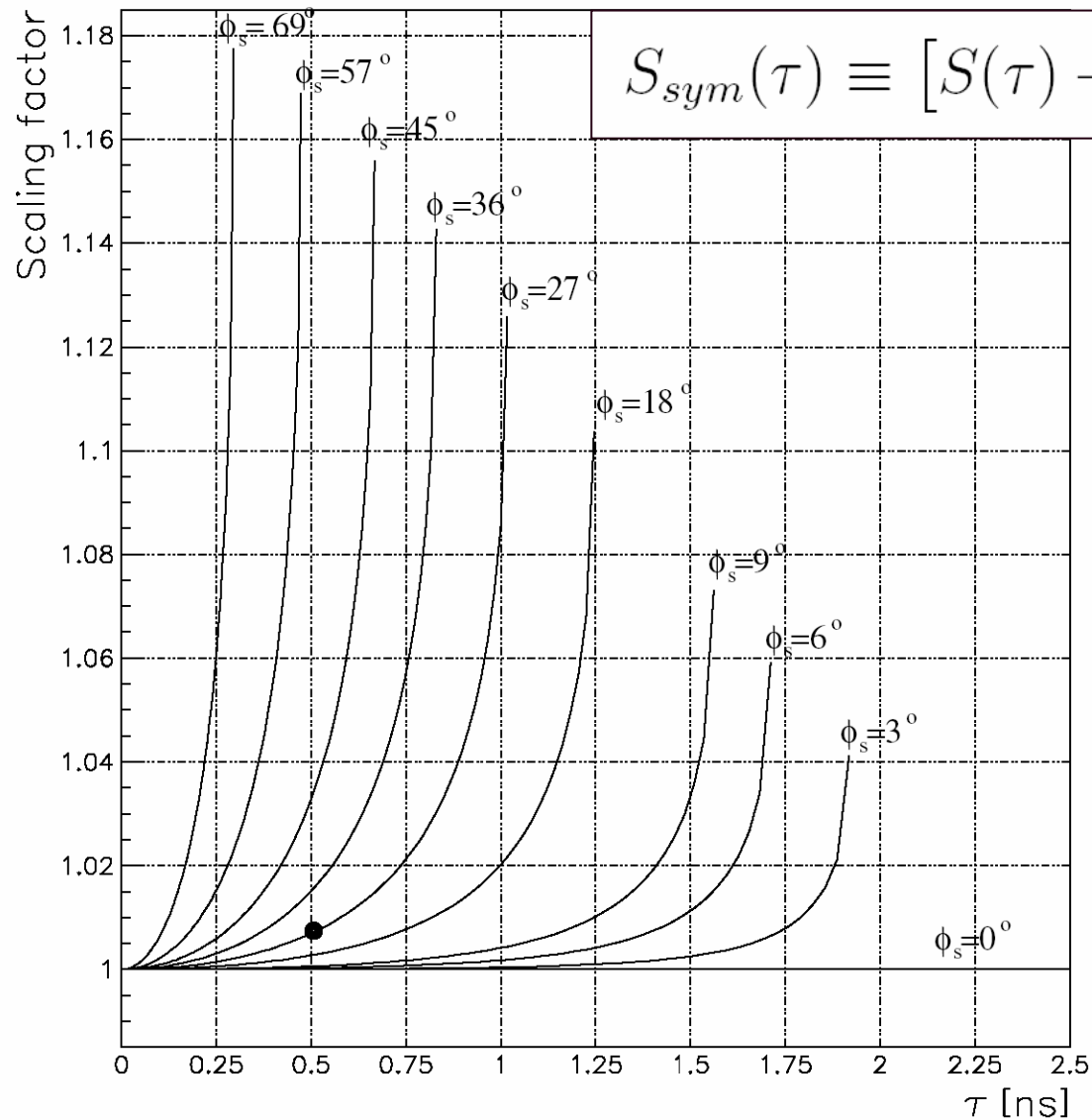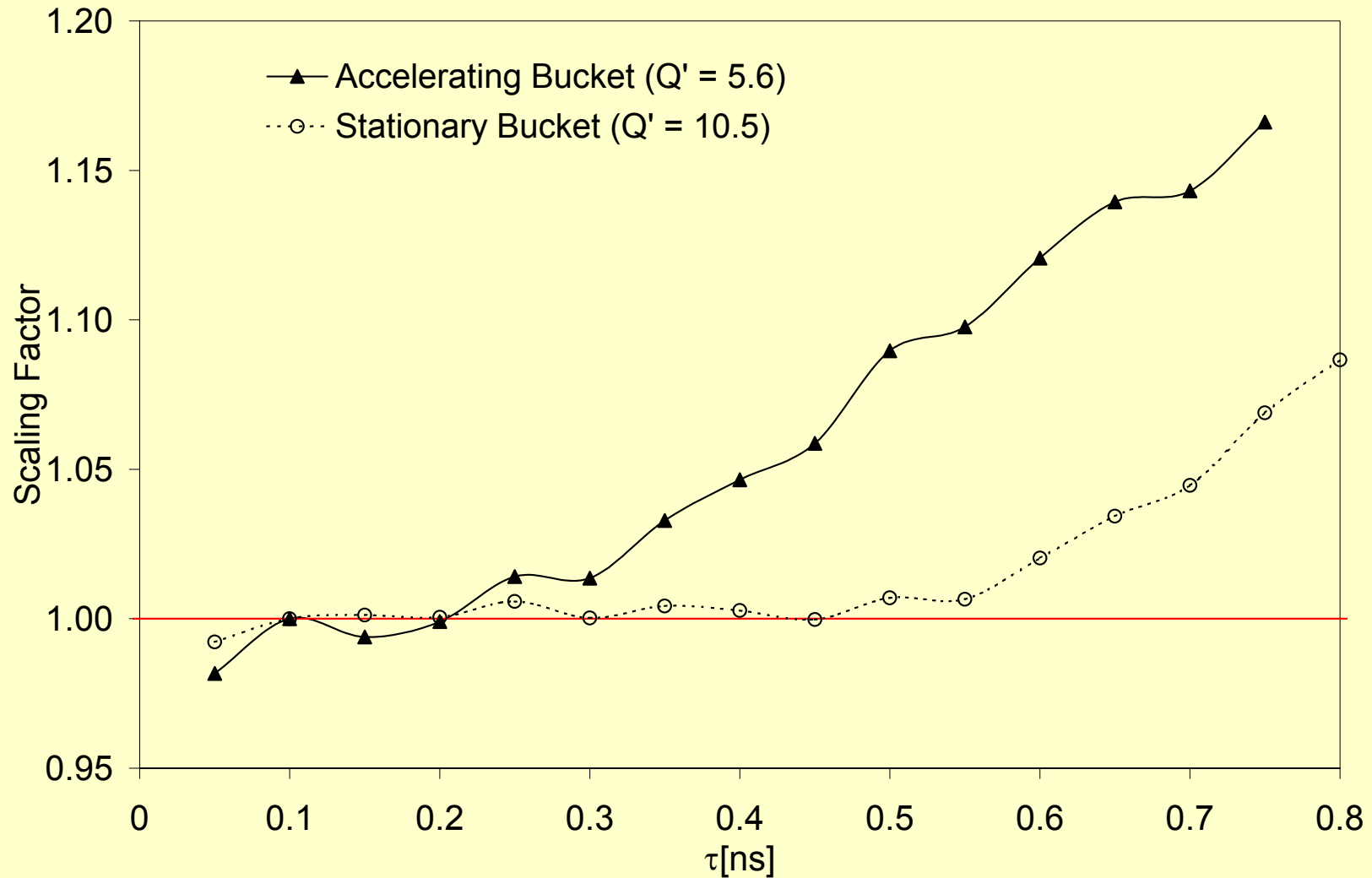# Effect of Acceleration

$$\Delta\phi_\beta^{\max}(\hat{\tau}) = S(\hat{\tau})\,\Delta\phi_\beta^{\max,\mathrm{lin.}}(\hat{\tau})$$

Effects of Acceleration (SPS Data)

Effect of Acceleration

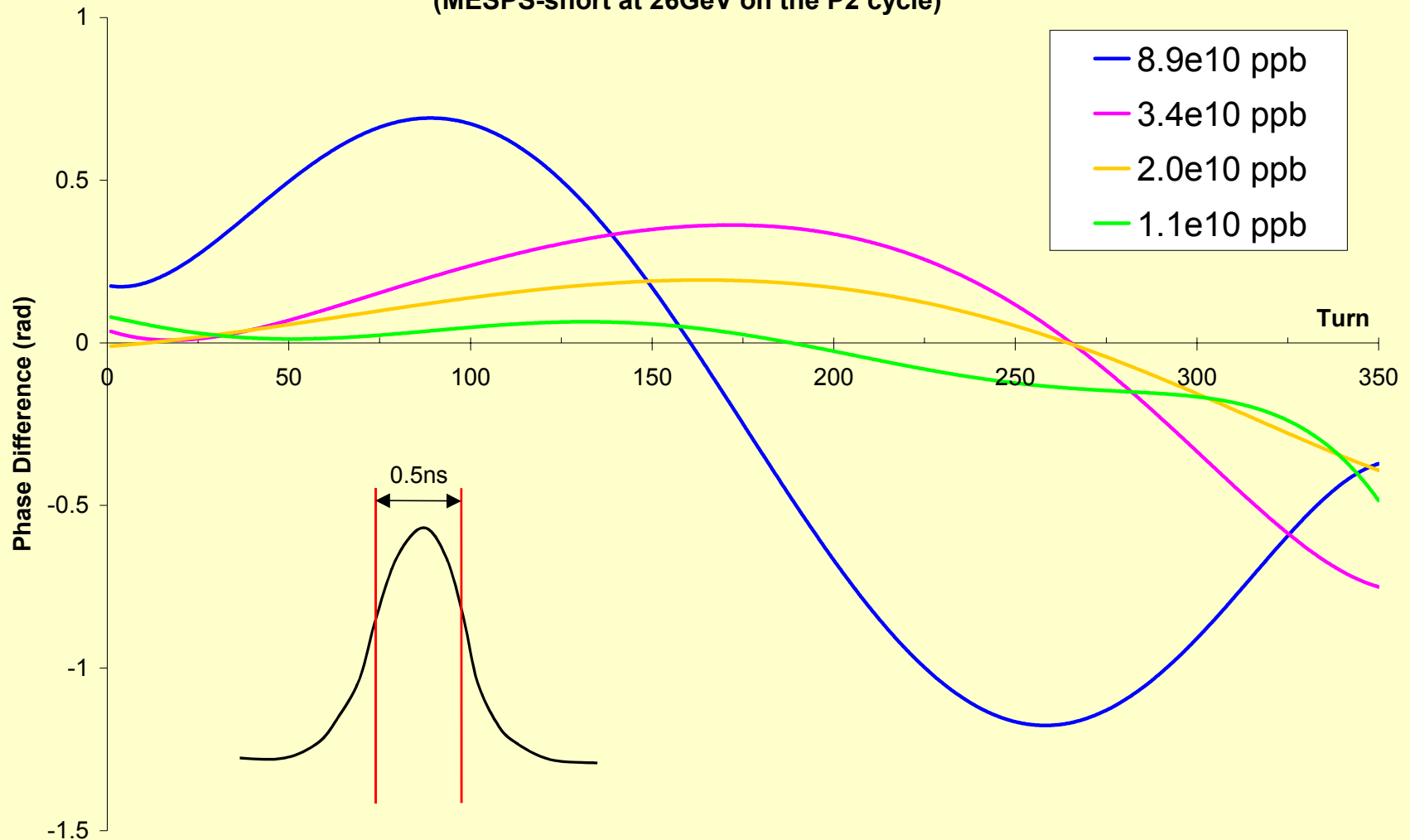$$S_{sym}(\tau) \equiv \left[S(\tau) + S(-\tau) \right]/2.$$
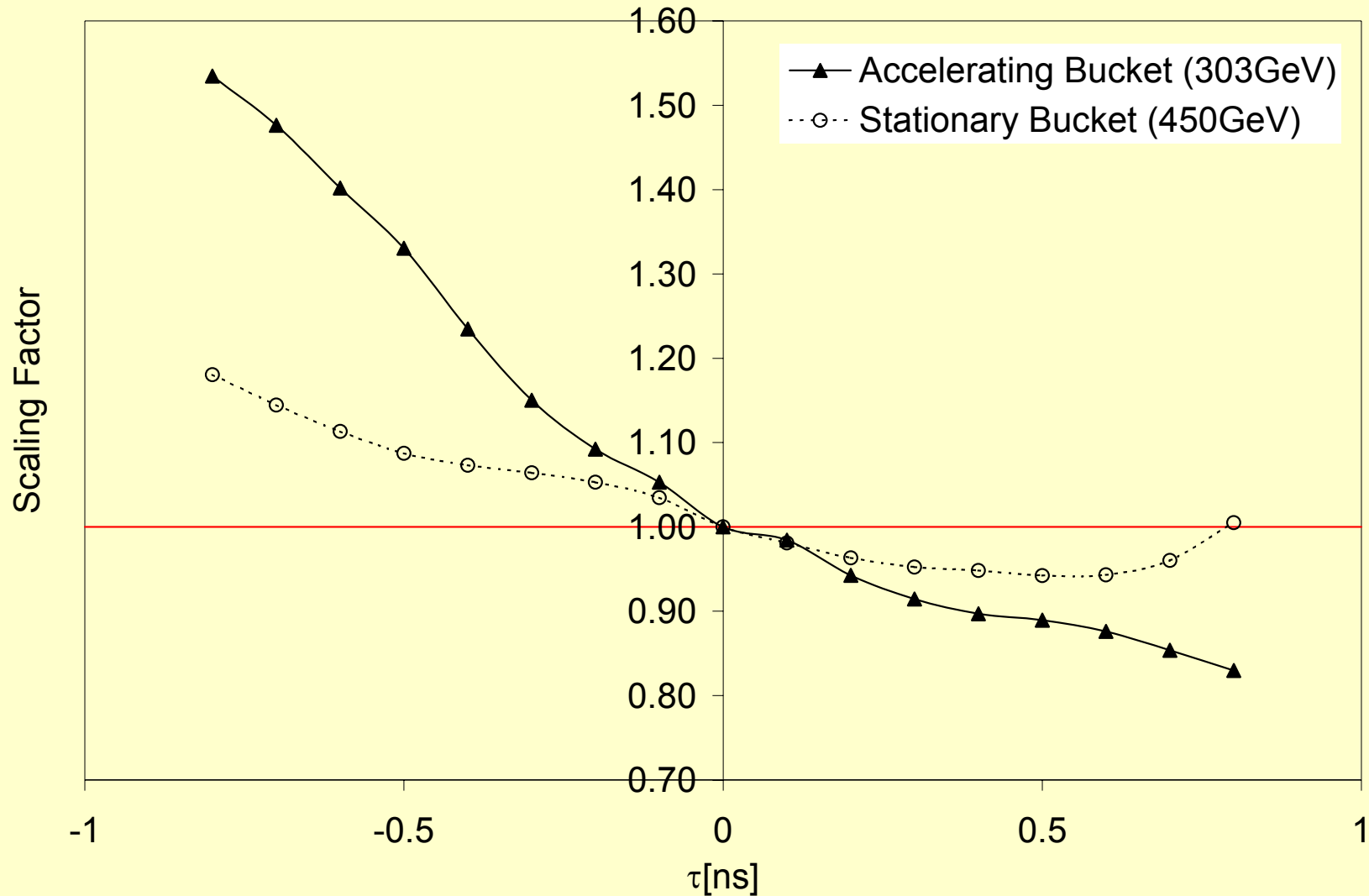
Effects of Acceleration (SPS Data)

SPS Impedance Effects at Low Energy

Change of Head-Tail Phase Difference with Intensity
(MESPS-short at 26GeV on the P2 cycle)

Conclusions

- Experimental
  - → Operational Head-Tail Q'-Meas. system demonstrated
  - → Technique also allows Q'' measurement
  - → Chromaticity measurement demonstrated at 0.5Hz
  - → Deconvolution required to remove perturbations due to hardware bandwidth limitations
  - → Useful instrument for other applications
    - transverse instabilities
    - possible use for SPS impedance measurements

- Theoretical
  - → Method applicable for both stationary and accelerating buckets
    - Experimentally verified with the constraint that the measurement be performed symmetrically about the bunch centre
  - → LHC robustness demonstrated for:
    - Non-linear chromaticity (Q'' and Q''')
    - Linear coupling (if arc-by-arc compensated as foreseen for LHC)
    - Impedance (by extrapolation from SPS to LHC)